UCRL- 94412
PREPRINT

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Topical Meeting on Short Wavelength Coherent Radiation
Optical Society of America
Monterey, California
March 24-27, 1986

March 1986

Lawrence Livermore National Laboratory

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ABSTRACT

We review progress in the modeling of Ne-like-Se XRLs. Dielectronic recombination plays an important role in the level kinetics as well as in ionization balance. Refraction becomes important at target lengths greater than 2cm by reducing signal at 0° view, and by having much larger signals emitted at a 10-20 mrad view. We predict success in scaling these systems to lower λ with higher Z targets, but at great cost in required driver power.

INTRODUCTION

A previous experimental series on the Novette laser, using a specially designed exploding selenium foil,[1] succeeded in demonstrating[2] laser amplification at 206 and 209 Å. The amplification was attributed to J = 2 to J = 1, 3p to 3s transitions in neon-like selenium. However, the theoretical foundation for predicted gain resulted in fundamental differences between data and theory.[1,3]

In this article, we review progress during 1985 that has advanced our understanding of the selenium x-ray lasing system. We also predict some potential successes and problems as we pursue the goal of demonstrating x-ray lasing at shorter wavelengths.

ATOMIC PHYSICS ISSUES

The major discrepancy between theory and data is the low gain observed on the J = 0 to J = 1, 3p to 3s transition compared to the predicted gain of about 10 cm^{-1}. In addition, the observed J = 2 to J = 1 gain was about 6 cm^{-1}, while the predicted value was 3 to 4 cm^{-1}.

The theory and predictions made last year contained at least one significant shortcoming. While it was widely recognized that dielectronic recombination could play an important role in atomic-level population kinetics, such recombination was only modeled in a crude manner. We used a reasonable guess as to the total rate, but connected that total rate from ground state to ground state of iso-electronic sequences. This rate was apparently correct because it reproduced gross features of n = 3 to n = 2 x-ray spectra that gave us an indication of ionization balance

*Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

(approximately 40% fluorine-like and 20% neon-like selenium). However, in dielectronic recombination (e.g., from a fluorine-like ion), a ground-state electron is elevated to an $n = 3$ level or higher, while a free electron decreases in energy by an equal amount, from the continuum into a high-lying level. While autoionization is the inverse process and can undo the doubly excited neon-like state, the ion can stabilize in other ways: in particular, by radiative stabilization. That process can leave the neon-like ion in a singly excited state. Cascade processes that follow favor populating the $J = 2$ levels over the $J = 0$ levels because of their higher (by a factor of 5) statistical weight. In addition, the 3s levels can be populated in this manner, thus lowering the gain on the $J = 0$ to $J = 1$, 3p to 3s transition. When we crudely modeled dielectronic processes by proposing that the flow from fluorine-like to neon-like is directly through their ground states, rather than (correctly) through excited states, we may have correctly predicted ionization balance, but eliminated the possibility of lowering $J = 0$ gain and raising $J = 2$ gains.

As a result of such deficiencies in previous theory, we have begun to include all the doubly excited states resulting from dielectronic recombination in the atomic physics input-data files. These files are read [along with hydrodynamic quantities from a two-dimensional (2-D) LASNEX simulation] into the XRASER computer code. With these new files, it is of interest to compare our new results for gain prediction with those of last year.

The 2-D LASNEX simulation models our nominal target, which consists of a 750-Å coating of selenium on 1500 Å of a plastic called formvar. A 2ω 2-beam Novette laser impinges on the foil with a line focus that is 200 μm in height at an intensity of 4×10^{13} W/cm^2 in a 450-ps, full-width-at-half-maximum (FWHM) Gaussian pulse.

The 2-D results do not differ fundamentally from those obtained by 1-D simulations[4]. However, the peak electron temperature for the 1-D simulation is somewhat higher than that predicted by the 2-D simulation. The temperature, density, and velocity history is fed into the XRASER calculation of gain, along with the detailed atomic physics model that includes most of the relevant doubly excited states formed by dielectronic recombination. For simplicity, we consider the conditions for a central computational zone that describes a typical part of the main lasing region.

The first result of interest from our calculation is that the ionization balance of 40% fluorine-like and 20% neon-like selenium is reproduced by the XRASER calculation, thus lending credence to our previous estimates. In Figs. a and b, we plot the prediction for gain vs time for the $J = 0$ to $J = 1$ and $J = 2$ to $J = 1$ lasers, respectively. Times early with respect to the peak of the driving laser pulse are largely irrelevant because the foil has not fully exploded. Thus, the initial high density and steep density gradients of the foil deny the laser system full access to gain down its full length, and refraction bends the laser out of the high-gain medium.[1,3] Times much later than the laser peak are uninteresting because the rapidly falling density leads to falling gain. The time of greatest interest is roughly the 100 ps immediately after the driving laser peak, which optimizes gain vs a nonrefractory density gradient.

At +100 ps in Fig. 1, the gain on J = 0 is about 7 cm^{-1}; the gain on the upper 209-Å J = 2 line shown in Fig. 2 is about 6.5 cm^{-1}. (The 206-Å J = 2 line has a similar gain.) Compared with our previous model, the J = 0 gain is slightly reduced due, in part, to a slightly higher 3s population. The J = 2 gain is nearly doubled, due to our directly populating the upper J = 2, 3p levels via the decay of the doubly excited states. Nevertheless, the predicted J = 0 gain remains too high with respect to the data. Although we have, as yet, no complete explanation for the discrepancy, we now have obtained a predicted gain for J = 0 that is comparable to that for J = 2, and the J = 2 predicted gain is now quite close to the observed value.

Another issue arising from our data is the apparent lack of lasing lines from fluorine-like states. Even with our recent and more complete modeling, we continue to predict a gain of about 2.5 cm^{-1} for fluorine-like lasing at 204 Å. While the value is significantly less than the gain of 6 cm^{-1} observed for J = 2 neon-like lines, it is curious that the lines remain unobserved given the large fraction of ions in the fluorine-like state.

HYDRODYNAMIC ISSUES

As another topic, we have performed studies of the laser medium under conditions that can be characterized as nonoptimal, i.e., arising from a subtle hydrodynamic effect. The nominal line focus of 1 cm is not uniform along the full 1-cm length. The laser intensity at the extreme edges of the 1-cm length is lower by a factor of 2 than that in the central part of the line of focus. This observation is based on both equivalent-plane optical measurements and on x-ray pinhole pictures. We have processed the LASNEX simulations at various intensities and created an x-ray pinhole calibration curve. From that curve and the experimental pinhole picture, we have confirmed that the laser intensity at the edge is one-half that at the center.

Figure 2 shows the density profile of an exploding foil 100 ps after the peak of a 220-ps, FWHM Gaussian driving laser pulse. The nominal intensity I_0 is 7 X 10^{13} W/cm^2. The profile for the intensity $I_0/2$ represents the density profile seen by the laser as it tries to exit the 1-cm-long tube (the intensity at the edge is reduced by a factor of 2). The outcome is not highly deleterious with respect to refraction. However, for an off-optimal shot, the central intensity may be $I_0/2$. In this case, the intensity at the edge is $I_0/4$, and the density profile at that edge shown in Fig. 3 is much steeper (more density) than the profile in the center of the lasing tube. The result can lead to deleterious refraction effects as the laser beam leaves the laser tube. This is a specific example of a general phenomenon: namely, off-optimal targets are increasingly sensitive to the I/2 edge effect.

BEAM PROPAGATION ISSUES

The Nova II target chamber will allow for two-sided illumination with a line focus of up to 5 cm in length. As we move to shorter-wavelength x-ray lasing schemes, our first priority is to reach saturation on our selenium scheme. Figure 3(a) shows the trajectories of x-ray laser beams as they traverse the length of the exploding foil for distances greater than 1 cm. The onset of severe degradation beyond 2 cm is quantified in Fig. 3(b).

From the trajectories of Fig. 3a another consequence emerges. Mentally, extend the target one more cm past 3cm. Clearly a zero degree (straight down the Z axis) view will collect little extra signal vis a vis a 2 or 3cm target due to refracton. However a view from 10 or 20 milliradians off axis can see orders of magnitude more signal. To demonstrate this, reflect Fig. 4a around Z = 0, from -2cm to 2cm. Then the "inverted rainbow" of rays (emerging at 10-20 mrad) all get a full 4cm worth of exponentiation. Thus during this time, there is far more signal at 10-20 mrad than there is at 0 mrad.

We are attempting to circumvent refraction limitations to reaching saturation by inventing new target geometries for the x-ray laser. One scheme involves exploding foils that face one another and explode toward each other. This scheme creates a temporary trench that traps the x-ray laser beam in a region of high gain and allows propagation over distances much longer than 1 cm. At 3 cm, we predict a degradation of only 10% compared to the 90% degradation for the single foil shown in Fig. 3(b). Preliminary hydroexperiments at KMS Fusion on this scheme support our optimism. However, the new target forms a confining trench in only one dimension. We are therefore pursuing cylindrical exploding foils as a 2-D analog of the trench targets. Other targets with tamping from thick formvar substrates also show promise as nonrefractory lasing media.

SHORTER WAVELENGTH LASING ISSUES

Shorter-wavelength schemes using nickel-like analogs to our neon-like system or rapid-cooling recombination schemes are currently under study and will be presented elsewhere. Here we present calculations for the gain of a higher-Z, neon-like system: namely molybdenum (Z = 42).

The nominal target is 1000 Å of molybdenum on 1000 Å of formvar. The target is irradiated by a 2ω laser with a total irradiance of 3.5×10^{14} W/cm^2 for 500 ps. At the peak of the driving laser, electron temperatures reach 2 keV, densities reach 5×10^{20} cm^{-3}, and the scalelength is about 200 μm. Lasing with a gain of about 3 cm^{-1} is predicted for both the J = 2 and J = 0 transitions.

An interesting change takes place in proceeding to higher Z. For selenium, the J = 0 was at 182 Å, shorter than the two J = 2 transitions at 206 and 209 Å. For molybdenum, the J = 0 at 139 Å is a longer wavelength than either of the two J = 2 transitions at 131 and 133 Å. The crossover occurs near yttrium (Z = 39). Moreover, the other J = 0 line (at 167 Å in Se) which was predicted to have a low gain in Se, is predicted to have gain of order 3cm^{-1} for Mo, and to be at about 105 Å. Reaching laser wavelengths in the "water-window" below 40Å will require laser powers far greater than currently available if we are to rely strictly on J = 2 Ne-like 3p-3s lasing. Using scaling laws for exploding foil targets[4], we find (details to be published elsewhere) the required driver power scaling as (XRL-wavelength)$^{-4}$. Ways of circumventing this obstacle are currently being studied.

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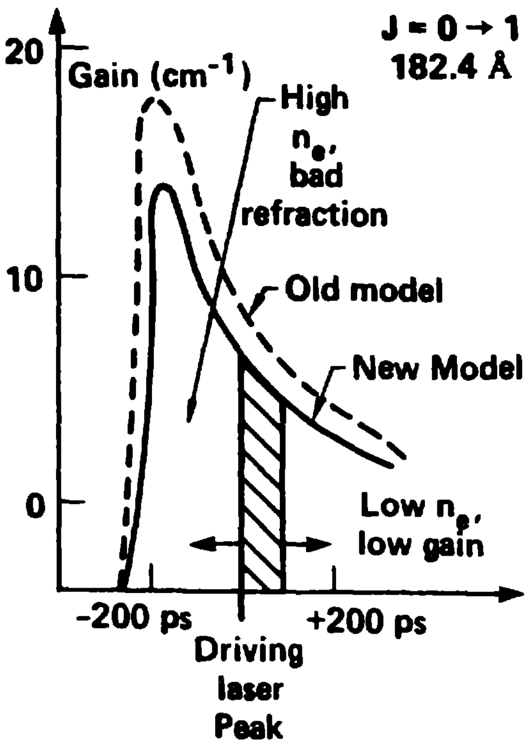


Fig. 1a. Predicated gain vs time for J = 0 to J = 1, 3p to 3s (183-Å) transitions in neon-like selenium.

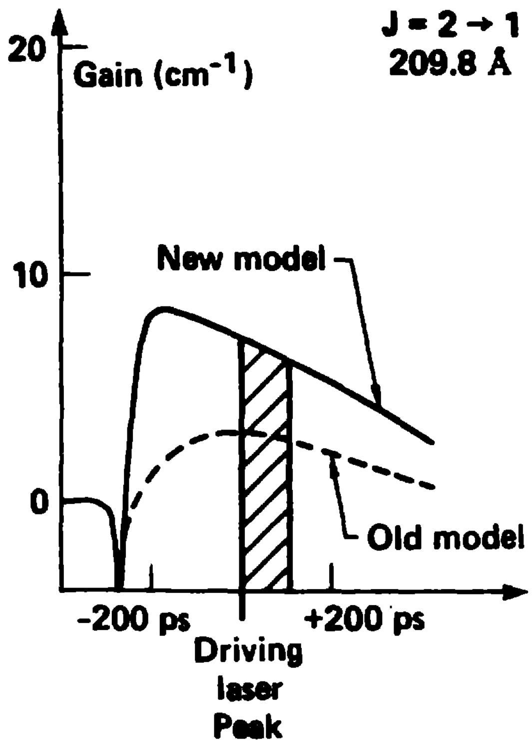


Fig. 1b. Predicated gain vs time for J = 2 to J = 1, 3p to 3s (209-Å) transitions neon-like selenium.

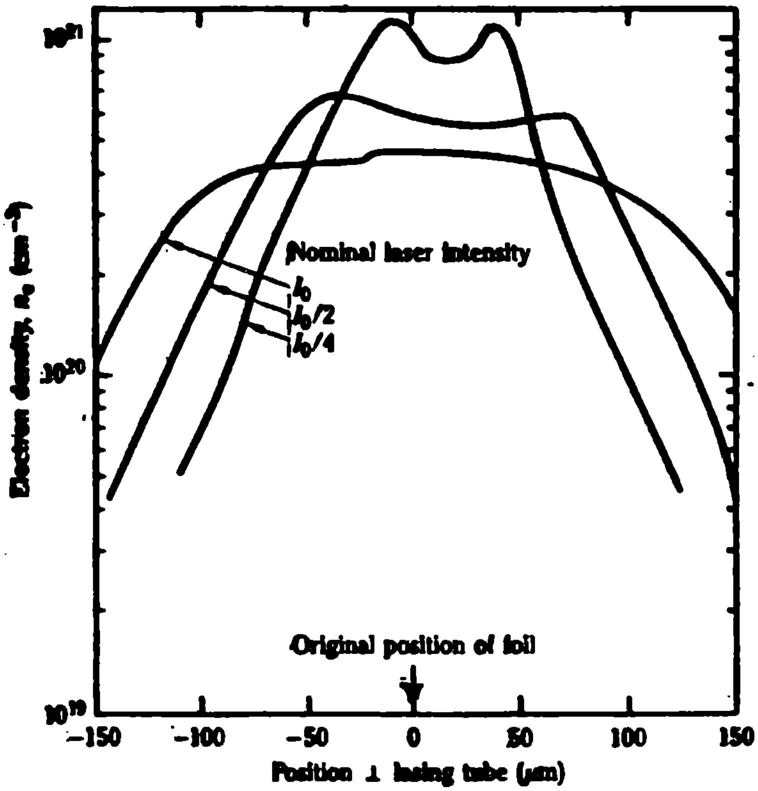
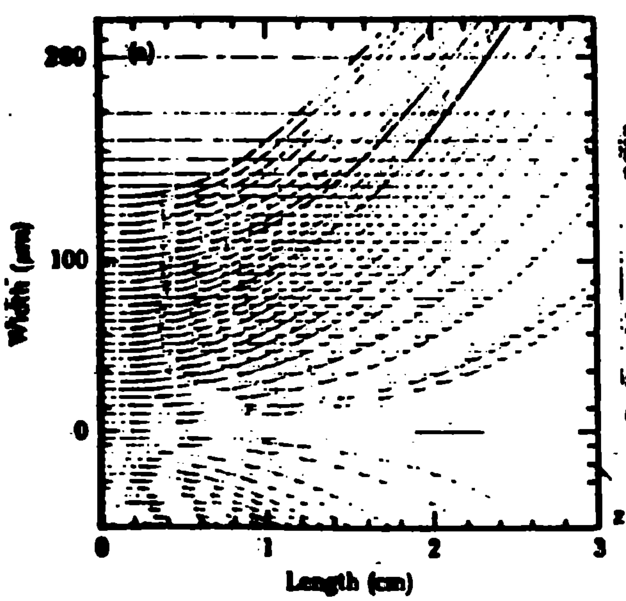


Fig. 2. Electron density vs position perpendicular to the lasing tube axis for three incident laser intensities.



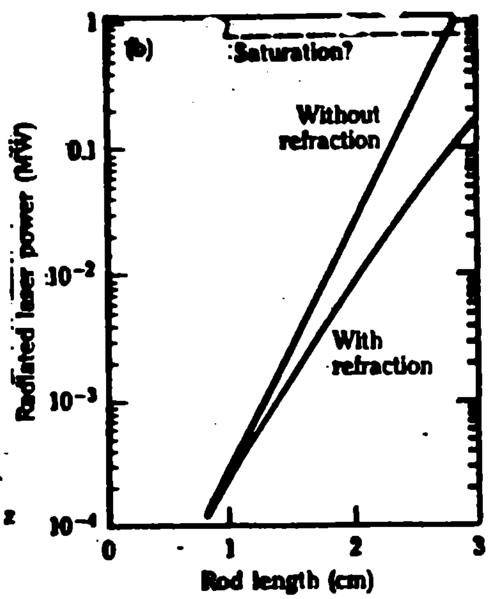


Fig. 3a. Trajectories of x-ray laser beam viewed from above an exploding foil and propagating over a distance of 3 cm.

Fig. 3b. Radiated laser power vs rod length calculated with and without refraction effects.